MERCURY MODELING FOR IMPROVED CRACK SIZING IN TUBING

Robert E. Shannon and Warren R. Junker
Westinghouse STC
1310 Beulah Road
Pittsburgh, PA 15235

Norio Nakagawa
Iowa State University - Center for NDE
1915 Scholl Road
Ames, IA 50011

Mohamod Behravesh
Electric Power Research Institute
P.O. Box 10412
Palo Alto, CA 94303

INTRODUCTION

The Westinghouse Science and Technology Center has successfully demonstrated that its patented mercury modeling technique provides a unique experimental bridge between tubing eddy current inspection conditions and analytical modeling efforts [1,2,3]. This approach is particularly useful for developing field inspection applications in nuclear steam generator tubing where the characterization of primary water stress corrosion cracking (PWSCC) has presented a challenge for eddy current inspection technology. Significant progress has been reported recently toward developing analytical models of the eddy current signal structure [4,5] and toward new techniques for inverting crack size from the eddy current signal structure. These models are presently limited in ability to represent real-life complexities, and they also must be experimentally validated. The mercury modeling approach permits the controlled study of an unlimited range of discontinuity morphologies and sizes, as well as steam generator structural and geometric factors. The mercury model is used in this study to investigate the effects of crack morphology on newly proposed eddy current length sizing techniques compared with current industry practices. The primary emphasis is to model cracks that more closely represent the morphology of PWSCC compared with ideal notch-like shapes. Effects of crack shape, crack face connectivity, and the presence of multiple initiation-sites are demonstrated.

While conventional bobbin coil inspections remain effective for quickly inspecting the large number of tubes in nuclear steam generators, the practice is limited for characterizing PWSCC. Alternatively, rotating pancake coils (RPC) and coil arrays (8x1) are increasingly being used for detailed PWSCC characterization. Length-based plugging limits based on RPC data have been adopted by some European utilities and are proposed for use in the U.S. to reduce the number of tubes requiring remedial action. However, studies of EC-predicted versus metallography-measured length on PWSCC samples suggest that crack morphology, orientation, closure, and possibly other factors reduce sizing accuracy in ways not fully understood. Further experimental studies aimed at advancing eddy current data collection and data analysis technology have been limited naturally by the difficulty in obtaining well-characterized samples containing the full range of conditions sufficient for a controlled scientific study.

The mercury modeling experimental data are compared also with analytical predictions obtained from a boundary-element method model [6,7] developed at the Iowa State University - Center for NDE (ISU-CNDE). The results show how to use new and existing length inversion techniques for sizing PWSCC in steam generator tubes.

EXPERIMENTAL TECHNIQUE

Mercury Modeling

The mercury modeling concept involves the use of liquid mercury to represent a fine-grained, non-magnetic structural metal. This concept is useful particularly for modeling steam generator tubing, because the electrical conductivity for mercury (μohm-cm) is approximately the same as that of Alloy 600 ($\simeq$100 μohm-cm). A flat plate mercury model, illustrated in Figure 1, was designed to provide a 10-to-1 scaling factor allowing accurate insertion of a variety of crack-like discontinuities. One face of the mercury model is designed with a replaceable surface made of a thin membrane, providing for probe lift-off as small as 0.5 mm. Crack models representing a range of crack lengths from 0.5 to 4.0 times the probe diameter were cut from 0.13 mm thick plastic shim stock to the desired size and shape.

The experiments were designed to study two basic probe designs: pancake coil probes and uniform field eddy current probes (UFEC). A 25.4 mm diameter air-core pancake coil

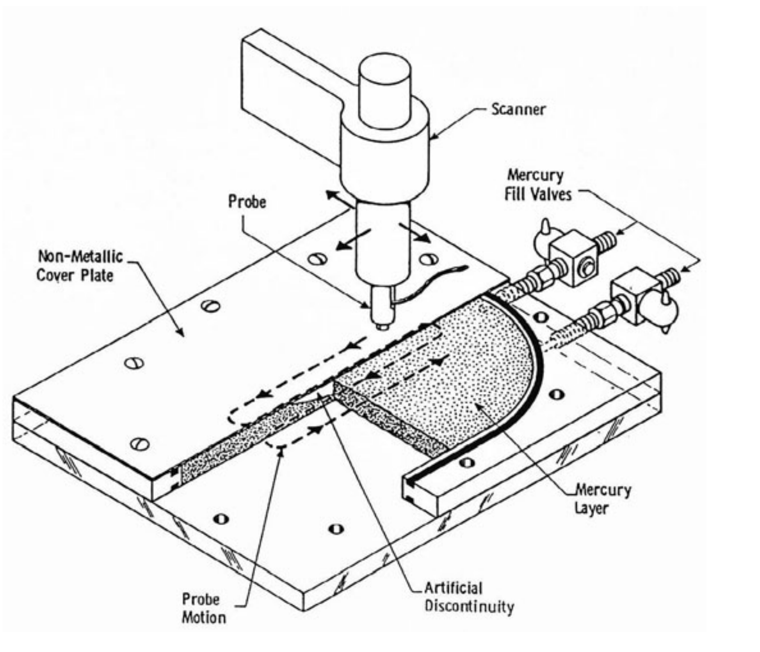

Fig. 1. Sketch of the Westinghouse mercury model for experimentally modeling eddy current responses from complex crack shapes.

probe was used to represent a typical RPC coil diameter of 2.54 mm. A UFEC probe was designed using a U-shaped ferrite core with 25.4 mm pole spacing for direct comparison with the pancake coil. Data collection was performed by scanning over the modeled crack in an X-Y pattern, while operating the eddy current instrument at coil excitation frequencies of 2, 4, 8, 16, 32, and 64 kHz. Because the mercury model frequency scaling factor is 1-to-100, this represents typical inspection frequencies of 200 to 800 kHz, and higher frequencies needed to fully evaluate the UFEC probe data.

Experience with pulled-tube samples has shown the key features of PWSCC to be: gradual tapering of the crack depth at crack ends; multiple initiation sites giving the appearance of smaller cracks aligned end-to-end; and the presence of crack interfacial ligaments. Crack end shape was modeled with simple shapes having different end profiles: square-corner rectangles (ideal EDM notches); round-corner rectangles (non-ideal EDM notches); and semi-circles (ideal cracks). PWSCC networking was studied by designing model cracks patterned after metallographic evidence from actual degraded tubes. More realistic PWSCC shapes were modeled with: two half-length semi-circles aligned end-to-end; and four quarter-length semi-circles aligned end-to-end. Connective ligaments were modeled with perforated rectangles, allowing 25% and 50% mercury contact on the crack face.

ANALYTICAL MODELING AND LENGTH INVERSION TECHNIQUES

The progress recently reported toward developing analytical models of the eddy current signal structure are useful in characterizing ideal-shaped crack lengths. Specifically, B. A. Auld et al. [4,5] reported improved sizing of ideal cracks based on inverting eddy current total impedance data. The method inverts an ideal crack's length by evaluating the eddy current total impedance data profile along the length of the notch. The proposed analytical length inversion techniques are called the slope-intercept method and the inflection point method, and are illustrated in Figure 2.

The analytical part of the present work is directed toward predicting eddy current responses for crack morphologies more complex than rectangular notches in a half plane. A set of computer codes has been developed under the sponsorship of ISU-CNDE, based on an analytical model using the boundary integral method adapted for electro-magnetism [6,7]. The version of the model computer program used in support of this effort was a code optimized for the half-space problem with tight cracks, allowing multiple cracks of fairly general shapes within a plane.

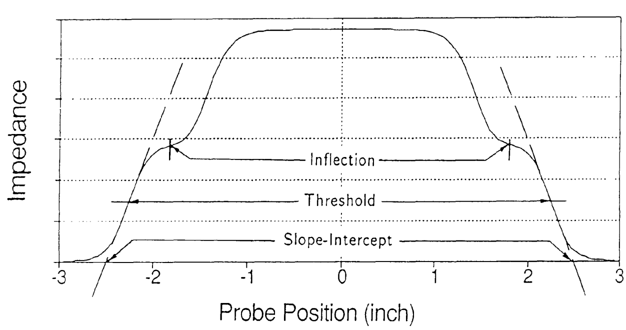

Fig. 2. Illustration of three different techniques for inverting crack length from eddy current amplitude profile data.

DISCUSSION OF RESULTS

Comparison of Mercury Model with Analytical Results

Analytical predictions for a pancake coil probe were calculated for various crack sizes and shapes using the ISU-CNDE model. Examples of the analytically predicted profiles of total impedance change versus probe position for 101.6 mm (4.0 in.) long rectangular and semi-circular cracks are presented in Figures 3 and 4, respectively. The experimental data points plotted from the mercury model results compare very closely to the analytical predictions for both crack shapes.

Figure 5 illustrates the effects of interfacial contact predicted by the analytical model for 25.4 mm long cracks at 8 kHz. Figure 6 shows the corresponding experimental results obtained by the mercury modeling technique and agree very well with the analytical results. The simple rectangular crack profiles (A) show a characteristic double-peak response for short (approximately one probe diameter) cracks. Figures 3 and 4 show that the peak amplitude of the eddy current signal decreases proportionally as the crack interfacial contact-area increases to 25% (B) and 50% (C).

Mercury Model Length Inversion Results

Length inversion data analyses were conducted using graphical plots of the horizontal channel, the vertical channel, and total impedance amplitude profiles. The vertical channel analyses are important because they relate directly to techniques typically used in tubing inspections. The 4 kHz data analyses results, corresponding to 400 kHz test frequency commonly used in tubing inspections, are presented in Figures 7 and 8 for the slope-intercept and 25% amplitude-threshold length inversion techniques. The inflection point technique was found to be of little practical use, because the eddy current amplitude profiles showed no inflection points corresponding to the ends of realistic crack shapes. The horizontal component amplitude results for all cracks were found to be essentially identical to the total impedance amplitude results which is a result of the very small phase rotation from horizontal at this frequency expected for near-side cracks.

The total amplitude data shows a linear fit between the eddy current crack length and the actual crack length using both the slope-intercept and amplitude-threshold techniques. A consistent tendency to oversize the crack length by approximately one coil diameter is shown. The vertical component also shows a fairly linear fit, with a greater tendency to

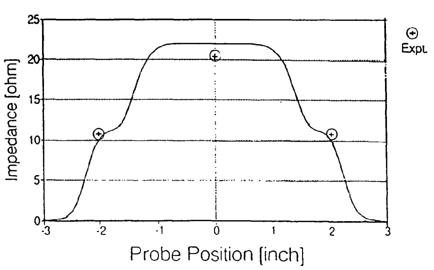

Fig. 3. Mercury model eddy current data points compared with the analytical model predicted amplitude profile (curve) for a 102 mm (4 in.) long rectangular notch.

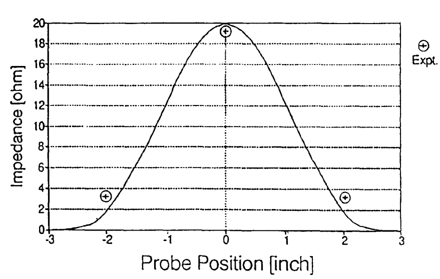

Fig. 4. Mercury model eddy current data points compared with the analytical model predicted amplitude profile (curve) for a 102 mm (4 in.) long semi-circular notch.

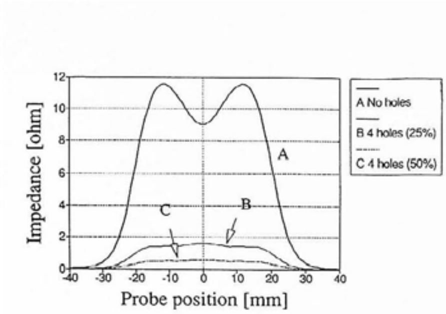

Fig. 5. Analytical model predicted amplitude profile for 25.4 mm long rectangular notch showing effects of 25% and 50% interfacial contact.

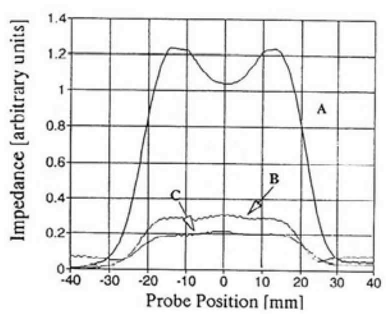

Fig. 6. Mercury model experimental amplitude profile for 25.4 mm long rectangular notch showing effects of 25% and 50% interfacial contact.

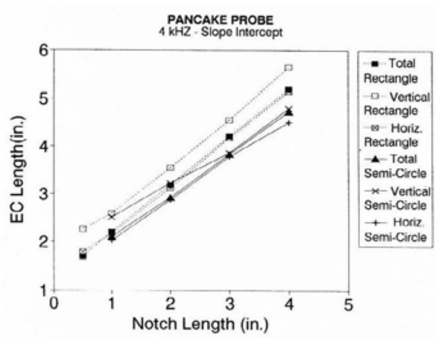

Fig. 7. Eddy current length inversion results for rectangular and semi-circular cracks using the slope-intercept technique on 4 kHz pancake coil data.

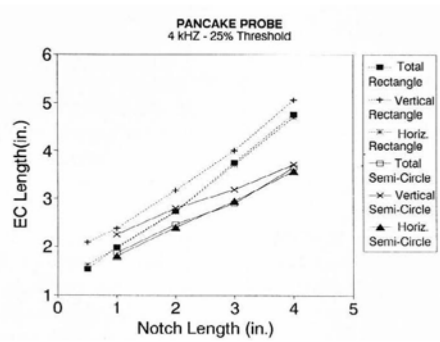

Fig. 8. Eddy current length inversion results for rectangular and semi-circular cracks using the amplitude-threshold technique on 4 kHz pancake coil data.

oversize, compared with the total amplitude results. Figure 7 shows a slight difference between the rectangular and semi-circular crack shape results when using the slope-intercept technique. Figure 8 shows that the effects of crack shape are much more pronounced when using the amplitude-threshold technique. The slope of the fit between eddy current measured crack length and actual crack length changed from approximately 1.0 for rectangular cracks to approximately 0.5 for semi-circular cracks. Also, the shortest semi-circular cracks are oversized, and the longest cracks are undersized.

The results for the 4 kHz experiments using a UFEC probe are presented for the slope-intercept and the amplitude-threshold techniques in Figures 9 and 10, respectively. Again, the horizontal component results are essentially identical to the total impedance amplitude results. The total amplitude results from the rectangular crack show a nearly ideal fit between measured and actual notch length, with a very small tendency to oversize. This is seen for both the slope-intercept technique and the amplitude-threshold techniques at 4 kHz. A slightly non-linear fit is shown for the rectangular notch length measurements using the vertical component. It is important to note that there was actually very little vertical

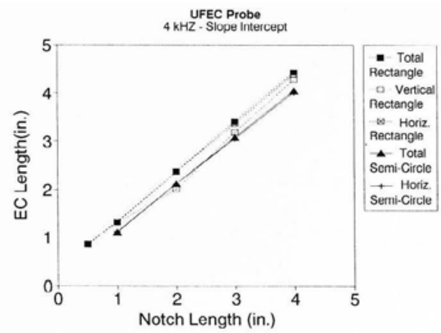

Fig. 9. Eddy current length inversion results for rectangular and semi-circular cracks using the slope-intercept technique on 4 kHz UFEC data.

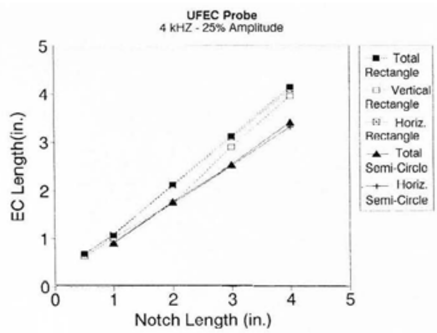

Fig. 10. Eddy current length inversion results for rectangular and semi-circular cracks using the amplitude-threshold technique on 4 kHz UFEC data.

deflection in the raw eddy current signal, resulting in a very low signal-to-noise ratio. The phase rotation away from lift-off (probe-wobble) is smaller at frequencies this low for the UFEC probe compared with the pancake coil design. The signal-to-noise ratio was sufficiently poor that no length measurements were possible for the semi-circular cracks using the UFEC probe. Figure 9 shows very little difference between the rectangular and semi-circular crack shape results when using the slope-intercept technique on the total impedance amplitude data. Figure 10 shows the effects of crack shape are again more pronounced when using the amplitude-threshold technique. The length measurements for semi-circular cracks are accurate at the shortest crack lengths but tend toward undersizing as the actual length increases. Overall, lower length measurement variations are observed from all of the modeled crack morphologies when using UFEC probe data compared with pancake coil results. Analyses based on vertical channel data exaggerated this effect.

A pancake coil calibration curve was developed from the rectangular crack (notch) results to represent the practice normally followed in tubing inspections. This calibration curve then was used to invert directly the mercury model data obtained from semi-circular cracks. A similar calibration was also developed for UFEC probe data. The resulting length errors for the slope-intercept technique and the 25% amplitude-threshold technique, are presented in Figures 11 and 12, respectively, in terms of equivalent crack sizes in steam generator tubing. As the actual crack length increases, the length sizing error using the slope-intercept sizing technique increases only very slightly. In contrast, the length sizing error using the traditional amplitude-threshold technique was found to be very dependent on the actual length of the crack. A significant observation from analyses of the UFEC data is a rotation in the apparent orientation of cracks with respect to the probe's orientation when used at the lower frequencies.

SUMMARY

The mercury modeling experimental results, and complementary analytical model results were evaluated to provide an assessment of the capabilities for measuring the size of steam generator tubing primary water stress corrosion cracking (PWSCC) from eddy current inspection data. The key results of this evaluation were:

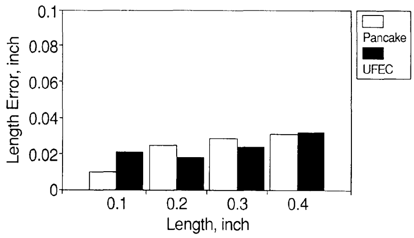

Fig. 11. Length inversion error for semi-circular cracks using the slope-intercept technique.

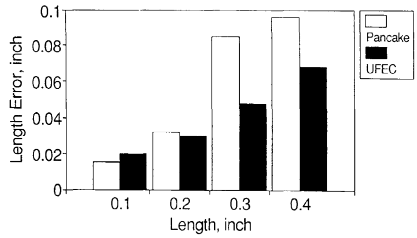

Fig. 12. Length inversion error for semi-circular cracks using the amplitude-threshold technique.

1. Two newly proposed techniques for inverting crack lengths from eddy current data were compared with the amplitude-threshold technique commonly used in tubing inspection practice:
   a. Length measurements are affected less by the shape of the crack using the slope-intercept technique when compared with amplitude-threshold technique.
   b. The amplitude-threshold technique is very sensitive to crack end shape (morphology) and the selected threshold level.
   c. The inflection point technique is of very limited use.

2. Performance of the uniform field eddy current probe design was compared with the pancake coil design used in RPC probes:
   a. Pancake coil probe experimental data agrees very well with analytical predictions.
   b. UFEC probe length measurement results showed the need for smaller correction factors compared with pancake coils.
   c. The UFEC probe results indicate potential difficulties in assessing the orientation of a crack.

3. Crack morphology has a significant effect on measured crack length:
   a. Crack length measurement errors depend on the shape of the crack ends, with tapered ends tending to result in undersizing.
   b. Crack length measurement errors caused by crack morphology can be minimized by using the slope-intercept technique.
   c. Experimental mercury model data confirm the analytical model predictions using both simple and complex crack shapes

ACKNOWLEDGMENTS

The authors thank L. W. Burtner, D. A. Chizmar, F. X. Gradich, and B. J. Sauka for their technical assistance. The data acquisition and other programming efforts performed at STC were carried out by T. W. Nenno. The work was supported by Electric Power Research Institute, Program S404-28.

REFERENCES

1. U. S. Patent No. 4,578,643.

2. W. R. Junker and B. J. Taszarek, "Liquid Metal Modeling of the Eddy Current Response." Materials Evaluation, The American Society for Nondestructive Testing, Inc., November, 1988, pp. 1564-1568.

3. W. R. Junker and W. G. Clark, Jr., "Experimental Modeling of Eddy Current Inspection Capabilities." In Review of Progress in Quantitative NDE, edited by D. O. Thompson and D. E. Chimenti, New York: Plenum Press, 1984, Vol. 3A, pp. 535-545.

4. B. A. Auld, G. McFetridge, M. Riaziat, and S. Jefferies, "Improved Probe-Flaw Interaction Modeling, Inversion Processing, and Surface Roughness Clutter." In Review of Progress in Quantitative NDE, edited by D. O. Thompson and D. E. Chimenti, New York: Plenum Press, 1985, Vol. 4A, pp. 623-634.

5. B. A. Auld, S. Jefferies, J. C. Moulder and J. C. Gerlitz, "Semi-Elliptical Surface Flaw EC Interaction and Inversion: Theory." In Review of Progress in Quantitative NDE, edited by D. O. Thompson and D. E. Chimenti, New York: Plenum Press, 1986, Vol. 5A, pp. 383-393.

6. N. Nakagawa, "Eddy-Current Detection Methods for Surface-Breaking Tight Cracks." In Review of Progress in Quantitative NDE, edited by D. O. Thompson and D. E. Chimenti, New York: Plenum Press, 1989, Vol. 8A, pp. 245-250.

7. N. Nakagawa, "Probability of Tight Crack Detection via Eddy Current Inspection." In Review of Progress in Quantitative NDE, edited by D. O. Thompson and D. E. Chimenti, New York: Plenum Press, 1990, Vol. 9A, pp. 893-899.